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Concentrating photovoltaic/thermal system with thermal and electricity storage: $CO_{2.eq}$ emissions and multiple environmental indicators

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ABSTRACT

The present article examines the environmental profile of a concentrating photovoltaic/thermal system with thermal and electricity storage. The system has been developed and experimentally tested at the University of Corsica, in France, and it combines non-concentrating photovoltaic modules with concentrating solar thermal. The study is based on life-cycle assessment according to global warming potential, cumulative energy demand, ReCiPe, Ecological footprint and USEtox. The results (phase of material manufacturing; scenario «without recycling») demonstrate that based on global warming potential, cumulative energy demand, most of the midpoint categories of ReCiPe, ReCiPe endpoint single-score, ReCiPe endpoint with characterization, Ecological footprint single-score (category of Carbon dioxide) and USEtox (category of Human toxicity/cancer), the aluminium support structure shows higher impact in comparison to the other components/materials of the system. Furthermore, the material manufacturing phase (scenario «without recycling») reveals that, in certain cases, the photovoltaic cells and the copper-based components present high impacts. More analytically, according to ReCiPe endpoint with characterization (scenario «without recycling»), the aluminium-based components (support structure;

receiver) present the highest DALY (disability-adjusted life years) and (species.yr) with total values of 0.015 DALY and 4.9×10^{-5} (species.yr). Regarding USEtox Ecotoxicity, the Noryl (for the pumps) shows an impact of 62.5 CTU_e that is considerably higher in comparison to the other components/materials of the system. The effect of recycling (metals; glass; plastics) has been examined and the results show that, by adopting recycling, energy payback time is reduced from 1.6 to 0.6 years and ReCiPe payback time is reduced from 17 to 8.4 years.

Keywords: Photovoltaic/thermal system; Sunlight concentration; Thermal storage; Electricity storage; Life cycle assessment; Scenarios with/without recycling

LIST OF SYMBOLS AND ACRONYMS

Related to methods and environmental indicators

CED	Cumulative energy demand
EF	Ecological footprint method
EPBT	Energy payback time
GWP 100a	Global warming potential based on a time horizon of 100 years
GWP 20a	Global warming potential based on a time horizon of 20 years
GWP 500a	Global warming potential based on a time horizon of 500 years
GWP	Global warming potential
IPCC 2013	IPCC 2013 method
LIME2	LIME2 method
ReCiPe PBT	ReCiPe payback time
ReCiPe	ReCiPe method
USEtox	USEtox method

Related to the equation of EPBT

E_{disp}	Primary energy for disposal

E_{inst}	Primary energy for system installation
E_{mat}	Primary energy for manufacturing (materials and collectors)
$E_{O\&M.a}$	Annual primary energy during use phase (operation and maintenance)
$E_{out.a}$	Annual output of the system (thermal and electrical energy) (converted into primary energy)
E_{transp}	Primary energy for transportation

Related to the equation of ReCiPe PBT

I_{disp}	Total score (in Pts, ReCiPe endpoint) for disposal
I_{inst}	Total score (in Pts, ReCiPe endpoint) for system installation
I_{mat}	Total score (in Pts, ReCiPe endpoint) for manufacturing (materials and collectors)
$I_{O\&M.a}$	Annual impact during use phase (operation and maintenance) (in Pts, ReCiPe endpoint)
$I_{out.a}$	Annual avoided impact due to use of PV electricity instead of using the electricity mix of a certain country (in Pts, ReCiPe endpoint)
I_{transp}	Total score (in Pts, ReCiPe endpoint) for transportation

Related to units

$CO_{2.eq}$	$CO_{2.equivalent}$
CTU_e	Comparative toxic unit for ecosystems
CTU_h	Comparative toxic unit for humans
DALY	Disability-adjusted life years
GJ_{prim}	$GJ_{primary}$
Pts	Points
(species.yr)	Loss of species over a certain area, during a certain time

Others

BA PVT	Building-added photovoltaic/thermal
BICPV	Building-integrated concentrating photovoltaic
BIPVT	Building-integrated photovoltaic/thermal
GHG	Greenhouse gas
HDPE	High-density polyethylene
LCA	Life cycle assessment
LCI	Life cycle inventory
PV	Photovoltaic
PVT	Photovoltaic/thermal

1. INTRODUCTION

PVT (photovoltaic/thermal) modules are devices in which PV (photovoltaic) panels and thermal units are mounted together. PVT systems convert solar radiation into electricity and heat and, therefore, they offer higher energy outputs in comparison to standard PV modules (which produce only electricity). There are different types of PVT configurations (PVT/air, PVT/water, natural or forced circulation, etc.) and they can be cost effective if the additional cost of the thermal unit is low. Moreover, PVT systems offer advantages from environmental point of view in comparison to standard PV systems (which produce only electricity) (Tripanagnostopoulos et al., 2005). In the light of the issues mentioned above, and by taking into account that solar systems offer a wide range of applications (for buildings (Tripanagnostopoulos et al., 2005), greenhouses (Esen and Yuksel, 2013), etc.), in the literature there are works about different solar systems (PVT, solar thermal, etc.) and some of these studies give emphasis on PVT environmental profile based on LCA (life cycle assessment).

A literature review about PVT LCA (Lamnatou and Chemisana, 2017) reveals that several investigations which include LCA/environmental issues about BA (building-added) PVT systems have been presented and most of these studies: 1) refer to domestic water heating (for the thermal part of the system) and include crystalline PV cells (for the PV part of the system), 2) examine EPBT (energy payback time), CO_2 emissions and cost issues. Some examples are the investigations of Tripanagnostopoulos et al. (2005; 2006), Kalogirou and Tripanagnostopoulos (2006), Dubey and Tiwari (2008).

On the other hand, a literature review about PVT LCA (Lamnatou and Chemisana, 2017) reveals that there are few investigations which include LCA/environmental issues about BIPVT (building-integrated photovoltaic/thermal) systems. These studies refer to PVT systems which include several types of PV cells and most of these works focus on air as working fluid, façade- and roof-integrated applications. In addition, most of these investigations examine EPBT, CO_2 emissions and economic issues (Lamnatou and Chemisana, 2017). For example, Chow and Ji (2012) presented LCA about different types of PVT systems. EPBTs of 2.8 and 3.8 years were found (for BA PVT and BIPVT, respectively). Kamthania and Tiwari (2014) studied semi-transparent PVT (double-pass façade) configurations, based on EPBT and CO_2 mitigation. Lamnatou et al. (2017a) investigated, according to different methods (ReCiPe, USEtox, etc.), the environmental profile of a BIPVT module (in terms of the phase of material manufacturing). Rajoria et al. (2016) studied BIPVT configurations by evaluating issues such as EPBT and CO_2 emissions.

At this point it should be noted that in the specific case of LCA about PVT systems with batteries, there are few studies. Mudgil and Kamthania (2013) presented an investigation about a BIPVT system consisting of building materials, fan, PV cells, PV frame, battery, inverter and charge controller. Emphasis was given on embodied energy and EPBT. The results of Mudgil and Kamthania (2013) showed EPBTs ranging from 4.26 to 5.26 years, depending on the type of the PV cells. Another study is that of Hassani et al. (2016) about the environmental performance of nanofluid-based PVT systems in comparison to standard PV and PVT systems. Hassani et al. (2016) highlighted that the greatest part of the consumed energy is due to the lead-acid batteries and the PV cells.

Based on the references mentioned above and by considering that:

1) During the last years there is an increasing interest for PVT systems since they provide (with one single device) heat and electricity (Lamnatou and Chemisana, 2017).

2) There are few investigations which present LCA/environmental issues about PVT systems with batteries.

3) In the literature, most of the PVT LCA studies refer to CO_2 emissions and EPBT (Lamnatou and Chemisana, 2017) and there are few PVT LCA studies based on different methods (ReCiPe, USEtox, etc.) (Lamnatou et al., 2017a), it can be seen that there is a need for more investigations that examine PVT environmental profile according to multiple life-cycle impact assessment methods.

In the light of the issues mentioned above, the present article assesses the environmental profile of a PVT system with thermal and electricity storage, appropriate for BA and off-grid applications, based on multiple methods, environmental indicators, approaches and scenarios (with/without recycling, etc.). In this way, the present investigation goes beyond the PVT LCA studies which are based on embodied energy/embodied carbon and examines PVT environmental performance from different points of view (human toxicity, ecotoxicity, etc.).

2. MATERIALS - METHODS

According to ISO 14040:2006 and ISO 14044:2006, the following phases have been adopted: goal and scope definition, life-cycle inventory, life-cycle impact assessment and interpretation.

2.1. Functional units and boundaries

Certain results are presented based on one solar unit which has the characteristics that are presented in Table 1.

Table 1. Characteristics of one solar unit.

Electricity	1.28 kW_p
Thermal energy	3.75 kW_p
Surface of the PV cells	9.34 m^2
Surface of the thermal absorber	1.17 m^2
Surface of the mirrors	15.49 m^2

With respect to life-cycle calculations, the following phases have been considered:

- Material manufacturing (for the collectors (PV and thermal) and the additional components of the system).
- Manufacturing of the collectors (PV and thermal).
- Installation.
- Use/maintenance.
- Transportation.
- Disposal.

Nevertheless, it should be noted that some results are only for the phase of material manufacturing. In addition, it should be clarified that in certain cases the impact is presented: 1) per m^2 of surface of the mirrors, 2) only for the batteries (impact per kg of battery), 3) only for the storage tank (impact for a storage capacity of 300 l).

Some additional definitions about the boundaries: Processes and transportation directly related to the production phase, use phase and disposal of the studied solar system have been taken into account. The flows include acquisition of the raw materials (or other resources). Moreover, allocation has been taken into account.

2.2. Technical characteristics of the system

The PVT system can work based on different modes: 1) production of thermal energy (by means of solar thermal absorbers that offer sunlight concentration), 2) production of electricity (by means of PV modules without sunlight concentration). The PVT system has been developed and experimentally tested at the University of Corsica, in France. There is thermal storage (by means of a storage tank) as well as electricity storage based on lead-acid batteries. Heat and electricity can be produced simultaneously or successively. A control system has been developed. The temperature control can be done by means of: flow rate variation, partial and progressive defocusing of the blades and connecting boilers in parallel and/or serial. It should be highlighted that the proposed system is appropriate for off-grid applications. Regarding thermal storage, there is a hot-water storage tank with a capacity of 300 l. For the circulation of the water, there are two water-circulating pumps. With respect to electricity storage, there are four batteries. Each battery has a nominal voltage of 12 Volt and a nominal capacity of 150 Ah.

In Figure 1, details about the PVT system can be seen. Regarding the modes of the system, it should be clarified that:

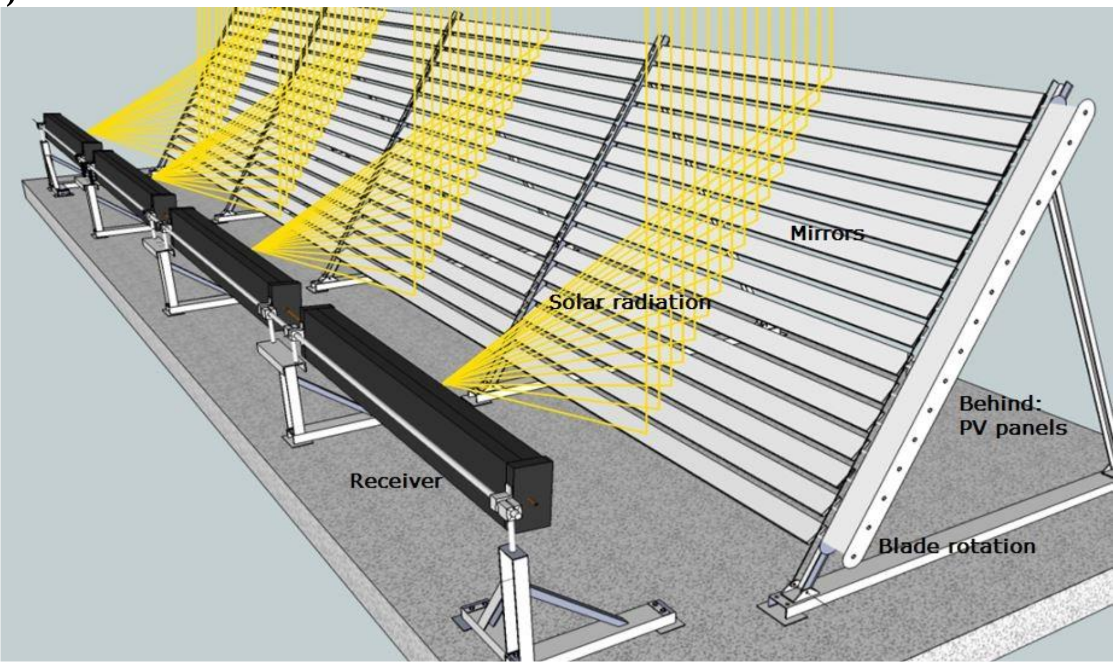
1) For the mode «only producing thermal energy» (Figure 1a), there is utilization of the entire surface of the mirrors. The mirrors have a total surface of 15.49 m^2 and they concentrate the sunlight onto four thermal absorbers. The four receivers/absorbers have been placed in front of the mirrors. In this way, the solar radiation that is reflected by the mirrors is concentrated onto the surface of the absorbers. In this case, the PV

modules are behind the mirrors (as it is indicated in Figure 1a) and are not used. The geometrical concentration ratio is around 13×.

2) For the mode «only producing electricity» (Figure 1b), there is utilization of the entire surface of the PV modules. In this case, the mirrors and the receivers/absorbers are not used and (as it is indicated in Figure 1b) the mirrors are behind the PV panels.

More details about the studied PVT system can be found in the study of Lecoeuvre et al. (2018).

a)



b)

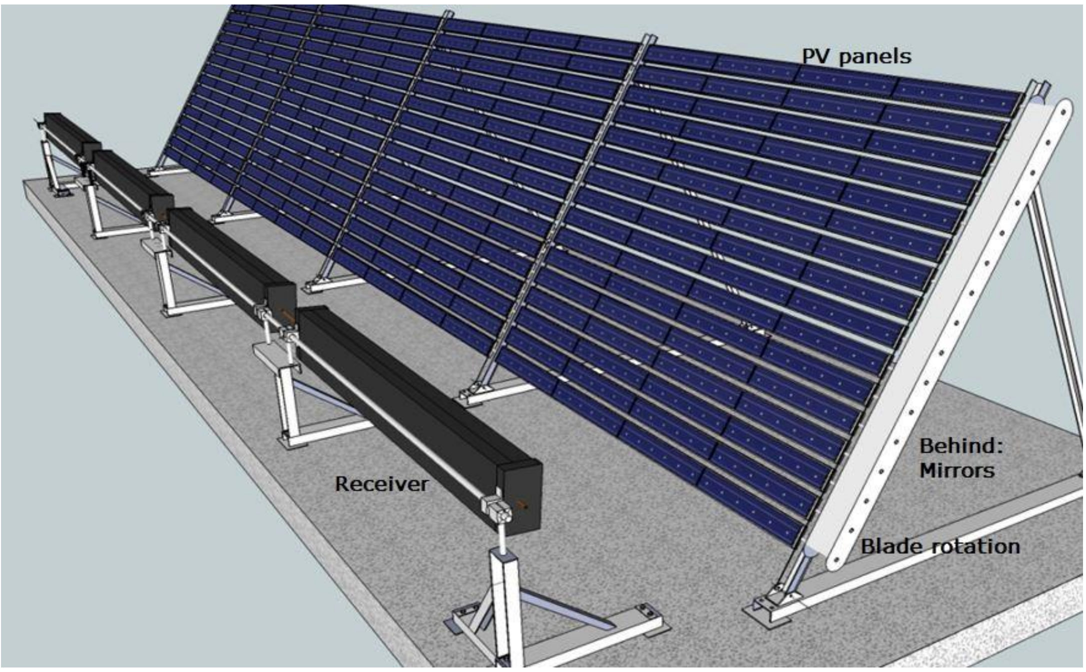


Figure 1. The PVT system developed at the University of Corsica, in France: a) Mode «only producing thermal energy», b) Mode «only producing electricity».

In Figure 2, the output (in terms of thermal energy and electricity) of the PVT system (climatic conditions: Ajaccio, France) is presented. These outputs refer to the following case: 4 hours per day the system is used for production of thermal energy (thermal mode) and the rest of the day it is utilised for production of electricity (PV mode). From Figure 2 it can be noted that the annual production is 996 kWh in terms of electricity and 2190 kWh in terms of thermal energy. With respect to the outputs mentioned above, the annual electricity production has been calculated by means of PVsyst software (Source: PVsyst). Moreover, the production of thermal energy has been estimated based on a thermal model which includes energy balance and considers mean daily irradiances.

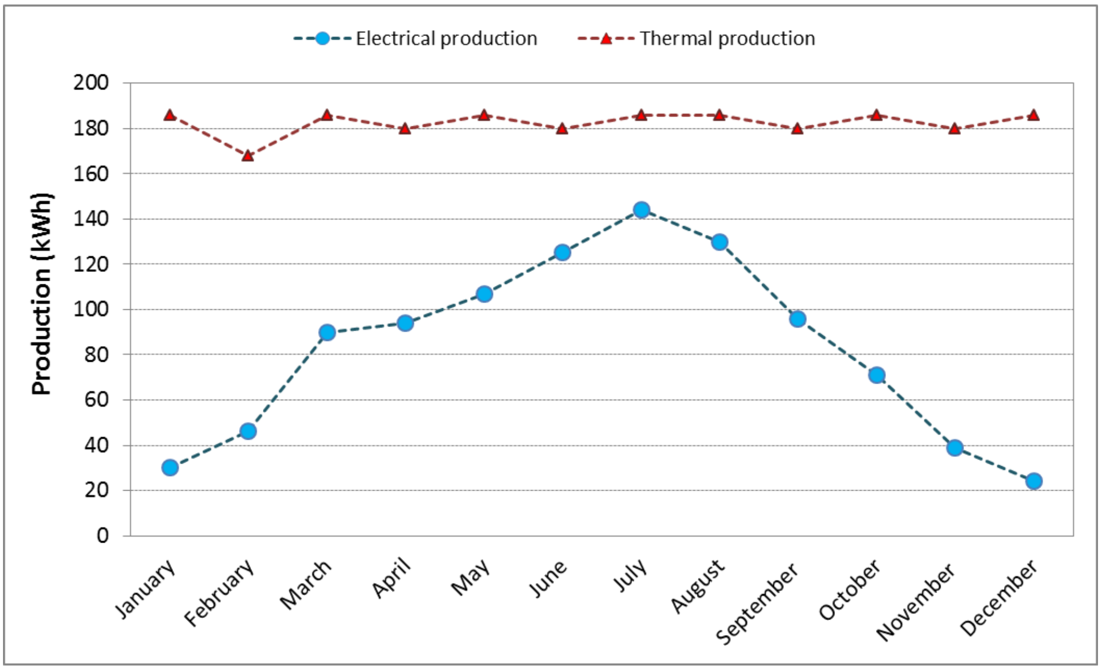


Figure 2. The annual output (in kWh, in terms of thermal and electrical production) of the PVT system. Climatic conditions: Ajaccio, France.

2.3. Assumptions

During the use phase, there are replacements of certain components of the PVT system: 1) one replacement of the batteries (optimistic scenario), 2) one replacement of the pumps. Moreover, general maintenance (for cleaning, etc.) has been taken into account (it has been assumed to be10% of the material manufacturing of the collectors: Lamnatou et al., 2014, 2016).

In terms of the lifespan, it has been assumed to be 20 years. According to the literature (Lamnatou and Chemisana, 2017), a lifespan of 20 years (for PVT systems) can be considered as reasonable.

With respect to the installation, the impact of the system installation has been assumed to be 3% of the total impact for manufacturing of the collectors and the additional components. The impact of the processes for manufacturing of the collectors has been assumed to be 27% of the impact that is associated with manufacturing of the materials of the collectors (Kalogirou, 2009; Lamnatou et al., 2014, 2016).

In addition, for the transportation of the materials/components, the following assumptions have been adopted: a distance of 50 km (from the factory gate to the building and from the building to the disposal site); transportation by means of lorry.

Concerning the phase of disposal, landfill has been assumed and includes the elements which are replaced over the lifespan as well as all the components of the PVT system (subsection 2.4).

Scenarios with recycling (for metals, glass and plastics) have been examined (in order to verify the environmental advantages that recycling offers for these types of solar systems which include large amounts of materials that can be recycled).

2.4. LCI (life cycle inventory), equations and data sources

SimaPro 8 (a software that is robust and reliable) (Source: SimaPro) and the database ecoinvent 3 (a database that is comprehensive and consistent with relevant data and high-quality datasets for LCI) (Source: ecoinvent) have been adopted. In Table 2, details in terms of the components/materials of the PVT system are presented. Regarding the support structure (mass: 295.27 kg aluminium), it includes multiple aluminium components (holding bars, blades, boxes, fittings, screw bars, etc.). Concerning the batteries, their LCI is according to the study of McManus (2011).

Table 2. LCI: Components/materials of the PVT system and their masses.

COMPONENTS/MATERIALS	REFERENCE	MASS (kg)
Support structure (aluminium)	Present study	295.27
Reflective surface (glass)	Present study	116.16
Reflective surface (aluminium)	Present study	0.84
Concentrating solar thermal: absorber (glass)	Present study	11.76
Concentrating solar thermal: absorber (aluminium)	Present study	52.85
Concentrating solar thermal: absorber (glass wool)	Present study	4.95
Concentrating solar thermal: absorber (copper)	Present study	2.46
Photovoltaics (multi-crystalline cells)	Present study	3.27
Photovoltaics (glass cover)	Present study	122.88
Storage tank (copper heat exchanger)	Present study	10.73
Storage tank (steel)	Present study	47.94
Storage tank (polyurethane foam)	Present study	5.56
Storage tank (plastic)	Present study	25.77
Screws (steel)	Present study	2.90
Pumps (brass)	Present study	1.40
Pumps (noryl)	Present study	0.70
Tubes (copper)	Present study	8.59
Tubes (rubber insulation)	Present study	3.21
Batteries (lead)	McManus (2011)	113.63
Batteries (oxygen)	McManus (2011)	4.23
Batteries (polyethylene)	McManus (2011)	3.43
Batteries (polypropylene)	McManus (2011)	12.58
Batteries (sulfuric acid)	McManus (2011)	19.28
Batteries (unsalted water)	McManus (2011)	31.64
Batteries (copper)	McManus (2011)	0.02
Batteries (glass)	McManus (2011)	0.04

For EPBT evaluation, the following equation (Lamnatou et al., 2014, 2016) has been used:

$$EPBT = \frac{E_{in}}{E_{out.a} - E_{O\&M.a}} = \frac{E_{mat} + E_{inst} + E_{transp} + E_{disp}}{E_{out.a} - E_{O\&M.a}} \quad (years) \qquad (1)$$

where,

E_{in} represents the total inputs (in terms of primary energy) for the manufacturing of the materials, the collectors, the batteries and the additional components of the system as well as the total inputs (in terms of primary energy) for the installation of the system, the transportation and the disposal.

$E_{out.a}$ stands for the annual output of the system (in terms of thermal and electrical energy) (converted into primary energy).

$E_{O\&M.a}$ is the annual primary energy during use phase (operation and maintenance).

E_{mat} represents the primary energy for material manufacturing (materials of the collectors, the batteries, the additional components of the system, etc.) as well as manufacturing of the collectors.

E_{inst} is the primary energy needed for the installation of the system.

E_{transp} stands for the primary energy for the transportation of the materials/components from the factory gate to the building and from the building to the disposal site.

E_{disp} is the primary energy needed for the disposal of the components/materials at the end of their life.

In the same way, for the calculation of ReCiPe PBT (ReCiPe payback time) the following equation has been adopted (Lamnatou et al., 2017b):

$$\text{ReCiPe PBT} = \frac{I_{mat} + I_{inst} + I_{transp} + I_{disp}}{I_{out.a} - I_{O\&M.a}} \qquad (years) \tag{2}$$

where I is the total endpoint ReCiPe score (in Pts) in terms of: material manufacturing (materials: collectors, batteries, additional components of the system, etc.) (I_{mat}); system installation (I_{inst}); transportation (I_{transp}); disposal (I_{disp}); annual avoided impact due to the use of PV electricity instead of utilizing the electricity mix of a certain country (in the present study, France´s electricity mix has been adopted) ($I_{out.a}$); annual impact during use phase (operation and maintenance) ($I_{O\&M.a}$).

The PBTs have been evaluated based on Barnwal and Tiwari (2008) (an investigation about PVT systems). The electrical output has been converted into equivalent thermal output, by utilizing the value of 0.38 that is the electric power generation efficiency of a conventional power plant (Huang et al., 2001; Barnwal and Tiwari, 2008). For the evaluation of $E_{out.a}$ (which, for EPBT, represents the avoided primary energy for the production of the same quantity of energy delivered by the solar system (Zambrana-Vasquez et al., 2015)) and $I_{out.a}$ (for ReCiPe PBT), it has been assumed the utilization of an electric-resistance water heater with 90% efficiency (U.S. Department of Energy, 2016) as well as the electricity mix of France (Sources: SimaPro 8; ecoinvent 3).

Concerning the impact of the batteries, it has been incorporated into E_{mat} (for EPBT) and I_{mat} (for ReCiPe PBT), based on Mudgil and Kamthania (2013) (a study about EPBT and embodied energy of a BIPVT system with batteries).

2.5. Scenarios

In Table 3, the adopted scenarios are presented. In addition, justifications about the selection of these scenarios and comments are provided.

Table 3. Scenarios that have been examined.

Scenarios	Justifications/comments
«With recycling» (for metals, glass and plastics) vs. «without recycling»	These scenarios have been examined in order to examine the effect of recycling (of certain materials)
GWP (global warming potential) time horizons: 1) GWP 20a 2) GWP 100a 3) GWP 500a	These scenarios have been examined in order to provide a broad picture about GWP since certain substances (associated with GWP) present a gradual decomposition and they become inactive on a long-term basis (PRé, 2014) GWP 100a is the most commonly used option (PRé, 2014)

2.6. Life-cycle impact assessment methods

The assessment of the environmental performance of the PVT system has been performed according to (Sources: SimaPro 8; ecoinvent 3):

1) IPCC 2013 GWP 20a V1.00; IPCC 2013 GWP 100a V1.00; IPCC 2013 GWP 500a V1.00

2) Cumulative Energy Demand V1.08 / Cumulative energy demand

3) ReCiPe Endpoint (H) V1.10 / Europe ReCiPe H/A (single-score)

4) ReCiPe Endpoint (H) V1.10 / Europe ReCiPe H/A (with characterization)

5) ReCiPe Midpoint (H) V1.10 / Europe Recipe H (with characterization)

6) Ecological footprint V1.01 / Ecological footprint (single-score)

7) USEtox (default) V1.03 / Europe 2004 (with characterization)

Some explanations (according to the report PRé (2014)) about the adopted methods are following presented:

- IPCC 2013 is about GWP based on different time horizons (20 years (GWP 20a); 100 years (GWP 100a); 500 years (GWP 500a)).

- CED (cumulative energy demand) is based on characterization factors for the energy resources divided in 5 impact categories which include non-renewable as well as renewable sources.

- ReCiPe includes impact categories based on midpoint and endpoint approaches. At the midpoint level, 18 impact categories are included. At endpoint level most of the midpoint impact categories are multiplied by certain damage factors and, then, they are aggregated into 3 endpoint categories (Human health, Ecosystems and Resources). At the endpoint level, the impact can be presented by means of Pts (points) that show the total environmental load as a single score (endpoint). The endpoint characterization factors can be described for human health by means of the number of years life lost and the number of years lived disabled (known as DALY (disability-adjusted life years)) and for ecosystems by means of the loss of species over a certain area, during a certain time (species.yr). In the present LCA study, the perspective H (hierarchist), that is based on the most common policy principles in terms of time-frame and other issues, has been adopted (in the case of ReCiPe) (PRé, 2014).

- Ecological footprint of a certain product is the sum of time integrated direct as well as indirect land occupation, regarding nuclear energy use and CO_2 emissions from fossil energy use.

- USEtox is about human and eco-toxicological impacts.

3. RESULTS AND DISCUSSION

3.1. Material manufacturing

Regarding the results presented in subsection 3.1, it should be clarified that they are about the phase of material manufacturing (components/materials of the PVT system: LCI presented in Table 2). The findings are illustrated in separate graphs (according to the adopted method). For these calculations, recycling has not been included. Moreover, it should be clarified that in Figures 3-7 and 8b certain components/materials (which show an impact above a certain value) are presented; however, calculations have been conducted for all the components/materials of the PVT system (LCI of Table 2).

3.1.1. GWP

In Figure 3, the findings in terms of GWP 20a, GWP 100a and GWP 500a are illustrated. In this figure, the components with GWP 100a higher than 0.1 t $CO_{2.eq}$ have been included. From Figure 3 it can be seen that:

1) With the increase of the time horizon, there is a decrease of the GWP, as it was expected (given the fact that certain substances (related to GWP) present a gradual decomposition and they become inactive on a long-term basis (PRé, 2014)).

2) Aluminium presents the highest GWP with total values ranging from 5.7 to 6.1 t $CO_{2.eq}$ (depending on the time horizon) for both aluminium-based components (support structure and receiver).

3) The PV cells show the second highest GWP (in this case the values vary from 1.4 to 1.8 t $CO_{2.eq}$).

4) Glass (for the reflective structure and the PV cover) and steel (for the boiler) present considerably lower GWP values in comparison to the aluminium-based components and the PV cells.

For aluminium (primary) the main part of the GWP is due to primary liquid aluminium and electricity inputs (Sources: SimaPro; ecoinvent). It is known that primary aluminium has high environmental impact and this is mainly associated with the high energy consumption and waste generation in comparison to secondary aluminium (Soo et al., 2018).

Regarding PV-cell impact, Hsu et al. (2012) presented a study about life-cycle GHG (greenhouse gas) emissions of crystalline-silicon PV electricity generation. It was highlighted that significant GHG emissions are attributed to silicon and wafer manufacturing utilised in the PV modules. Additional inputs (during manufacturing phase) such as silicon type and grid electricity GHG emission intensity may also contribute considerably, depending on the case (Hsu et al., 2012). Regarding the description of the life-cycle process, crystalline-silicon PV system includes the following phases: upstream, operation and downstream. The upstream phase refers to the acquisition of raw materials (silica sand, etc.) necessary for material manufacturing.

The next step includes the energy inputs which are needed in order to process the materials mentioned above into other materials (crystalline silicon, etc.). In addition, energy inputs are necessary for the manufacturing of the components of a PV system (Hsu et al., 2012).

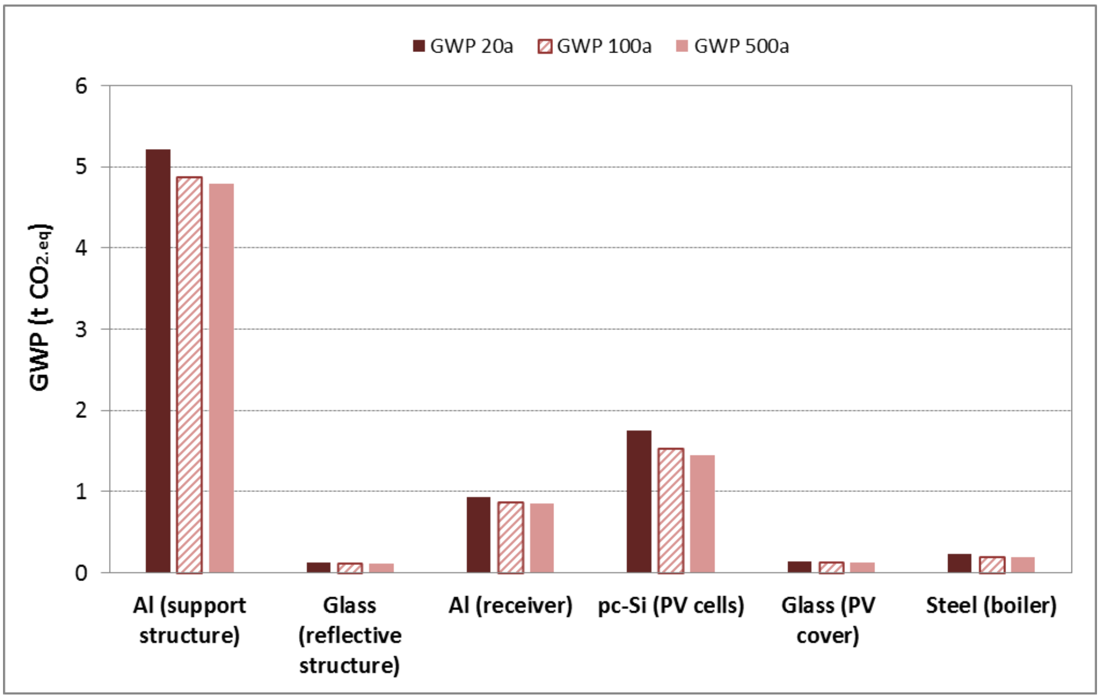


Figure 3. GWP (20a, 100a, 500a): Phase of material manufacturing for certain components/materials of the PVT system, based on the LCI of Table 2.

3.1.2. CED

In Figure 4, the results according to CED are illustrated. In this figure, the components which present CED values more than 1 GJ_{prim} have been included. From Figure 4 it can be seen that aluminium shows the highest CED with a total value of 60.3 GJ_{prim} (for both the aluminium support structure and the receiver). The PV cells are responsible for the second highest CED (22.3 GJ_{prim}). Glass (for the reflective structure and the PV cover), steel (for the boiler) and HDPE (high-density polyethylene) (for the boiler) present a total CED of 7.7 GJ_{prim}. Furthermore, from Figure 4 it can be noted that the CED of the aluminium support structure is almost double than the CED of the PV cells.

It should be noted that the high CED of the primary aluminium is mainly associated with the production of primary liquid aluminium and the high inputs in terms of electricity in aluminium industry. Concerning PV-cell impact, the high CED is mainly related to silicon solar grade and silicon wafer during PV-cell manufacturing phase (Sources: SimaPro; ecoinvent). Additional discussion about primary aluminium and PV-cell impact has been presented in subsection 3.1.1.

With respect to CED, Huijbregts et al. (2010) conducted a comprehensive analysis of potential similarities and differences between several life-cycle impact assessment methodologies and CED. It was noted that there is a high correlation between the various methodologies (that have been evaluated) and CED. This demonstrates that, despite the fact that there are different philosophies and complexity of the methodologies compared, they produce a comparable ranking in terms of commodity production impacts (Huijbregts et al., 2010).

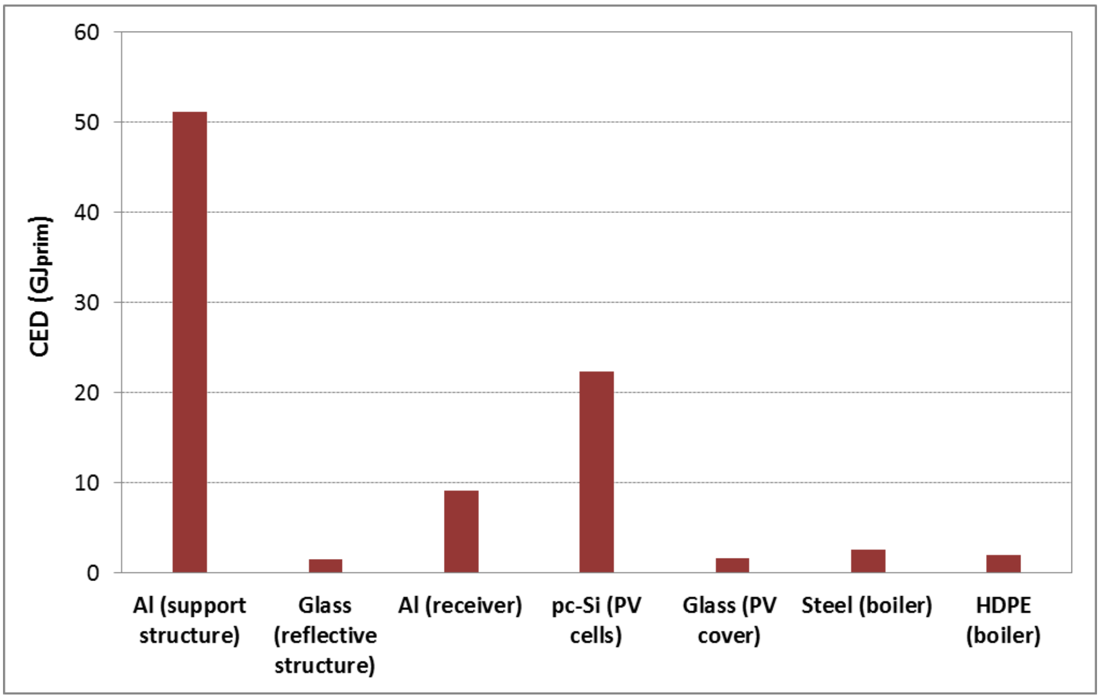


Figure 4. CED: Phase of material manufacturing for certain components/materials of the PVT system, based on the LCI of Table 2.

3.1.3. ReCiPe endpoint single-score

In Figure 5, the findings according to ReCiPe endpoint approach (single-score) are illustrated. It should be clarified that in Figure 5 have been included the components/materials which show more than 5 Pts for Human health. From Figure 5 it can be noted that:

1) The impact category with the highest score is the one of Human health and that with the second highest score is the one of Resources.

2) The impact category of Ecosystems, in general, present scores which are considerably lower in comparison to Human health and Resources, especially for the steel- and copper-based parts of the PVT system.

3) Aluminium (for the support structure and the receiver) shows the highest score. More analytically, the total values (for both the aluminium support structure and the receiver) are 293 Pts for Human health, 107 Pts for Ecosystems and 145 Pts for Resources.

4) Copper (for the receiver, the boiler and the tubes) presents the second highest score. In this case it should be highlighted that there is a remarkable difference between the scores for the categories of Human health and Resources and the scores for the category of Ecosystems.

5) The PV cells are responsible for the third highest score (73 Pts for Human health, 32 Pts for Ecosystems and 48 Pts for Resources).

6) By focusing on the three components/materials with the highest impact (aluminium, copper, PV cells), it can be seen that Human health is the category with the highest score (471 Pts). Resources and Ecosystems present 304 and 144 Pts, respectively.

As it was previously discussed (subsections 3.1.1 and 3.1.2), the impacts (for material manufacturing phase) mentioned above are related to: i) aluminium (primary) liquid and electricity inputs for aluminium (primary), ii) copper concentrate for copper (primary), iii) silicon wafer and silicon solar grade for PV cells (Sources: SimaPro; ecoinvent).

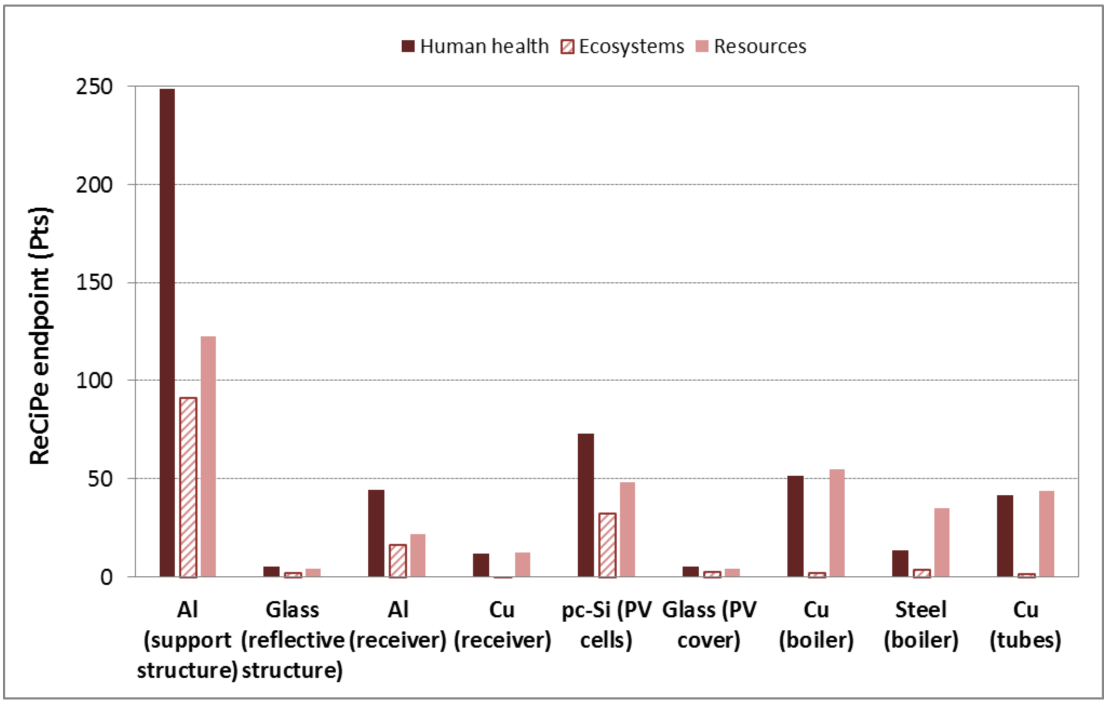


Figure 5. ReCiPe endpoint single-score (Human health, Ecosystems, Resources): Phase of material manufacturing for certain components/materials of the PVT system, based on the LCI of Table 2.

3.1.4. ReCiPe endpoint with characterization

In the present subsection, results according to ReCiPe endpoint with characterization, separated according to DALY and (species.yr), are presented.

In the graphs have been included the components with higher than 0.002 DALY and higher than 1.0×10^{-6} (species.yr). From Figures 6a and 6b it can be observed that:

1) The components with the highest DALY and the highest (species.yr) are the aluminium-based (the support structure and the receiver) ones with total values of 0.015 DALY and 4.9×10^{-5} (species.yr).

2) The components with the second highest DALY are the copper-based ones (the boiler and the tubes) with a total value of 0.005 DALY. Moreover, for (species.yr) the PVs are responsible for the second highest impact with a value of 1.5×10^{-5} (species.yr).

3) The PV cells present the third highest DALY (0.004). Glass (for the reflective structure and the PV cover) shows the third highest (species.yr) with a total value of 2.2×10^{-6} (species.yr).

It should be clarified that for aluminium (primary), for the PV cells as well as for glass the greatest part of DALY is due to the category of Climate change/human health. Moreover, for copper (primary) the major part of DALY is because of the category of Human toxicity. Furthermore, for all the materials mentioned above (aluminium (primary), PV cells, glass, copper (primary)) the greatest part of (species.yr) is due to the category of Climate change/ecosystems.

With respect to DALY, Kobayashi et al. (2015) presented a work about assessing burden of disease as DALY in LCA. It was noted that DALY quantifies endpoint indicators of the human burden of disease in LCA studies. A literature review of usage of DALY in LCA was presented and two prominent methods were identified (ReCiPe 2008 and LIME2). Kobayashi et al. (2015) highlighted that the concept of DALY seems to be beneficial given the fact that it offers direct comparison as well as aggregation of different health impacts.

a)

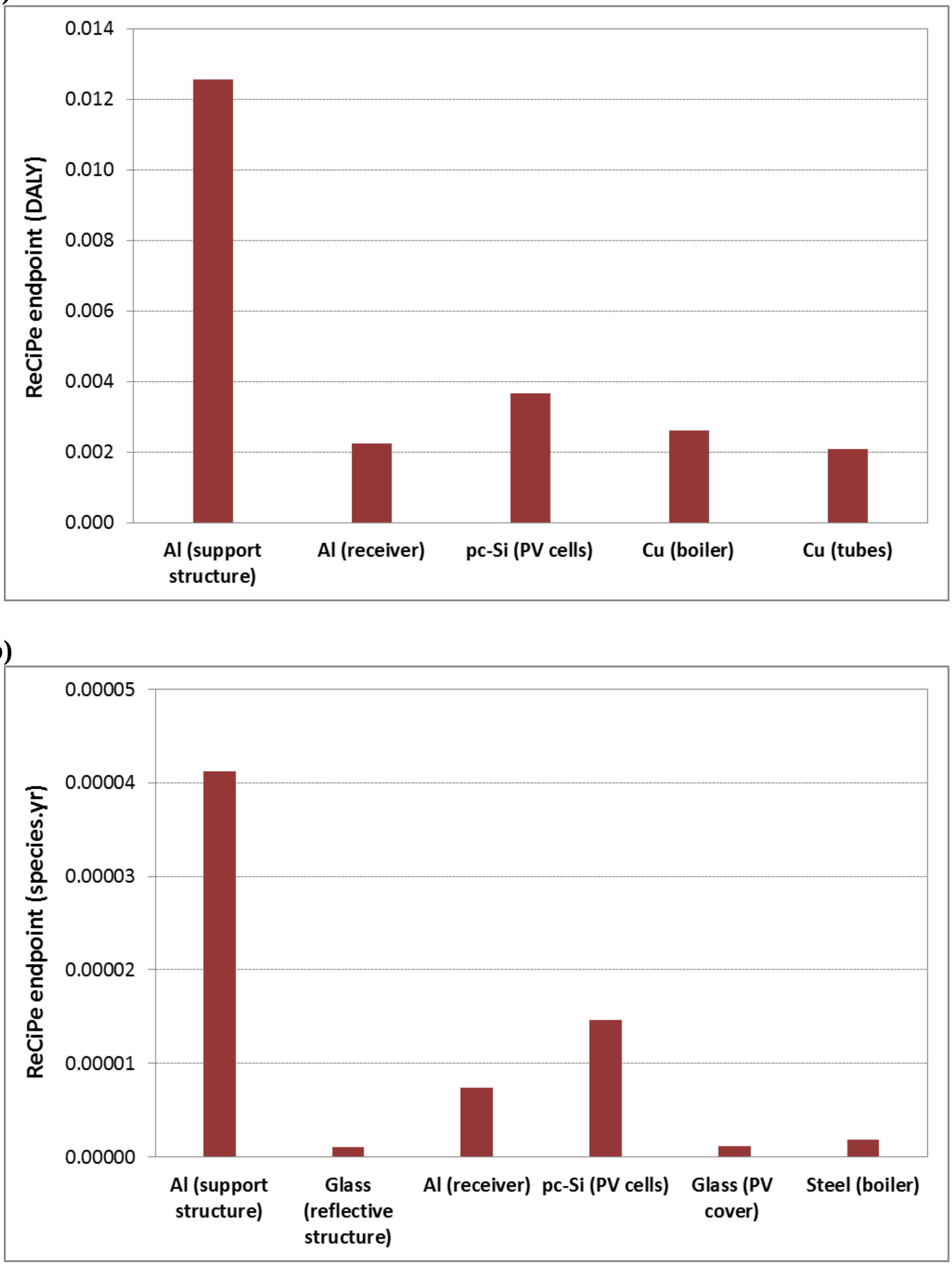


Figure 6. ReCiPe endpoint with characterization, in terms of: a) DALY, b) (species.yr). Phase of material manufacturing for certain components/materials of the PVT system, based on the LCI of Table 2.

3.1.5. ReCiPe midpoint with characterization

In Table 4, the results according ReCiPe midpoint with characterization, for the components with the highest impact for each category, are presented. From Table 4 it can be noted that:

1) The aluminium support structure presents the highest impact for 11 (Climate change, Terrestrial acidification, Freshwater eutrophication, etc.) out of 18 midpoint categories. Most of these midpoint categories, at the endpoint level, are associated with damage to human health and ecosystems.

2) The PV cells are responsible for the highest impact for 4 midpoint categories: Ozone depletion, Terrestrial ecotoxicity, Ionising radiation and Agricultural land occupation. Most of the 4 midpoint categories mentioned above, at the endpoint level, are responsible for impacts on human health and ecosystems.

3) Copper (for the boiler) shows the highest impact for 3 midpoint categories (Marine eutrophication, Human toxicity and Metal depletion) and most of these midpoint categories (at the endpoint level) are related to damages to human health and resources.

The midpoint approach has been adopted in order to identify which components/materials are responsible for the highest impact at the midpoint level. In addition, as it is noted in the report PRé (2014), the «problem oriented approach» defines the impact categories at a midpoint level and an advantage is the fact that the uncertainty of the results at this point is relatively low.

Table 4. ReCiPe midpoint with characterization: Phase of material manufacturing for certain components/materials of the PVT system, based on the LCI of Table 2. For each impact category the component with the highest impact is indicated.

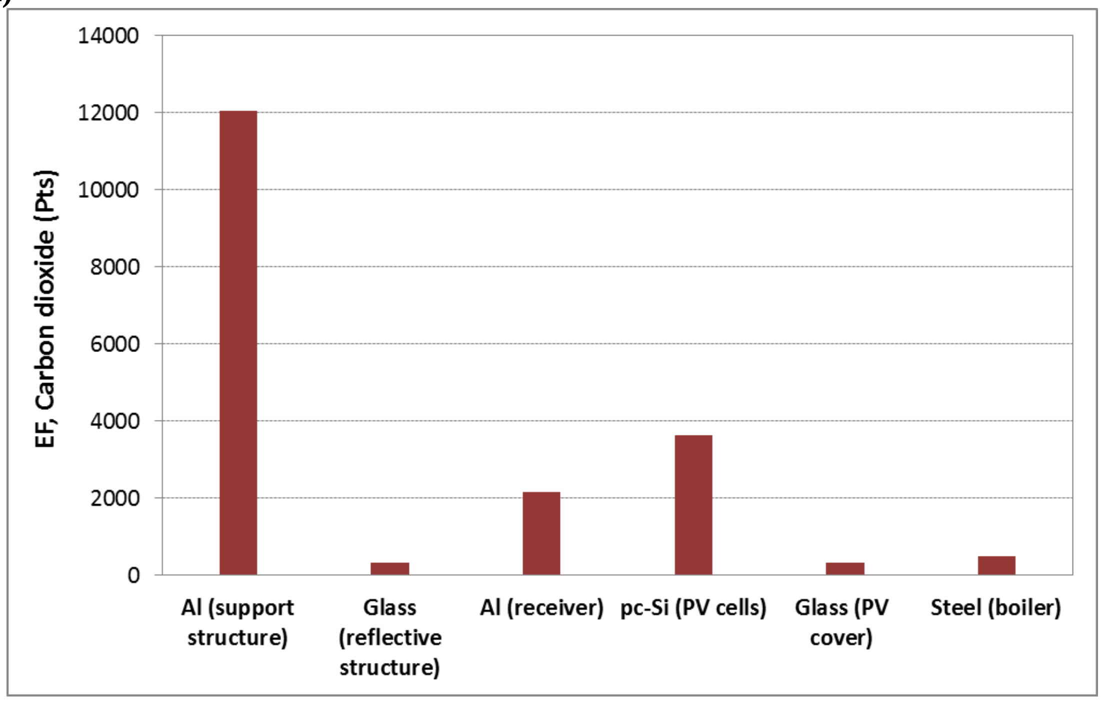
Impact category	**Component with the highest impact / Results**
Climate change	Aluminium support structure: 4877.1 kg CO_2 eq
Ozone depletion	PV cells: 3.9×10^{-4} kg CFC-11 eq
Terrestrial acidification	Aluminium support structure: 33.9 kg SO_2 eq
Freshwater eutrophication	Aluminium support structure: 2.7 kg P eq
Marine eutrophication	Copper (for the boiler): 2.4 kg N eq
Human toxicity	Copper (for the boiler): 3243.0 kg 1,4-DB eq
Photochemical oxidant formation	Aluminium support structure: 16.9 kg NMVOC
Particulate matter formation	Aluminium support structure: 15.1 kg PM10 eq
Terrestrial ecotoxicity	PV cells: 4.9 kg 1,4-DB eq
Freshwater ecotoxicity	Aluminium support structure: 70.8 kg 1,4-DB eq
Marine ecotoxicity	Aluminium support structure: 69.4 kg 1,4-DB eq
Ionising radiation	PV cells: 365.8 kBq U235 eq
Agricultural land occupation	PV cells: 102.4 m^2a
Urban land occupation	Aluminium support structure: 44.8 m^2a
Natural land transformation	Aluminium support structure: 0.5 m^2
Water depletion	Aluminium support structure: 43133.2 m^3
Metal depletion	Copper (for the boiler): 1144.9 kg Fe eq
Fossil depletion	Aluminium support structure: 1104.1 kg oil eq

3.1.6. Ecological footprint (EF)

Figure 7 presents the findings according to EF. Figure 7a is for Carbon dioxide (in the graph the components which present more than 300 Pts for the category of Carbon dioxide have been included). Figure7b is for Nuclear (in the graph the components which show more than 50 Pts for the category of Nuclear are illustrated). From Figure 7a it can be noted that for EF/Carbon dioxide the aluminium support structure presents the highest score (remarkably higher than the other components) and for EF/Nuclear the PV cells show the highest score. More specifically, for EF/Carbon dioxide the score of the aluminium support structure is around 3 times higher than that of the PV cells. On the other hand, for EF/Nuclear (Figure 7b), the total Pts for the PV cells are almost double than the total Pts for the aluminium support structure.

By taking into account all the components/materials of the system (Table 2), the results show the following total scores: 19827 Pts for EF/Carbon dioxide, 1495 Pts for EF/Nuclear and 503 Pts for EF/Land occupation. Therefore, it can be noted that Carbon dioxide presents around 13 times higher score than Nuclear and 39 times higher score than Land occupation.

a)



b)

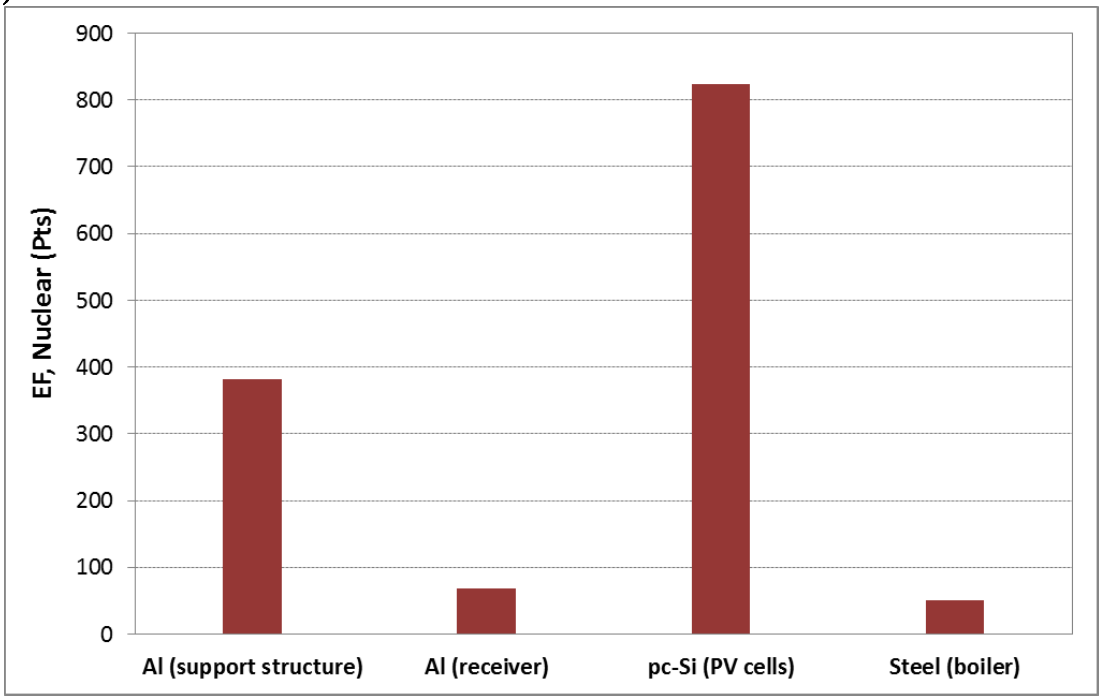


Figure 7. EF single-score in terms of: a) Carbon dioxide (Pts), b) Nuclear (Pts). Phase of material manufacturing for certain components/materials of the PVT system, based on the LCI of Table 2.

3.1.7. USEtox

In Figure 8, the findings based on USEtox are illustrated. Figure 8a is about Human toxicity (for all the components presented in Table 2) and Figure 8b is about Ecotoxicity (in the graph of Fig. 8b, the components with values more than 1 CTU_e have been included). From Figure 8 it can be seen that:

1) Regarding Human toxicity/cancer, the aluminium support structure, the PV cells and the Noryl for the pumps are the components/materials with the first, second and third highest values, respectively.

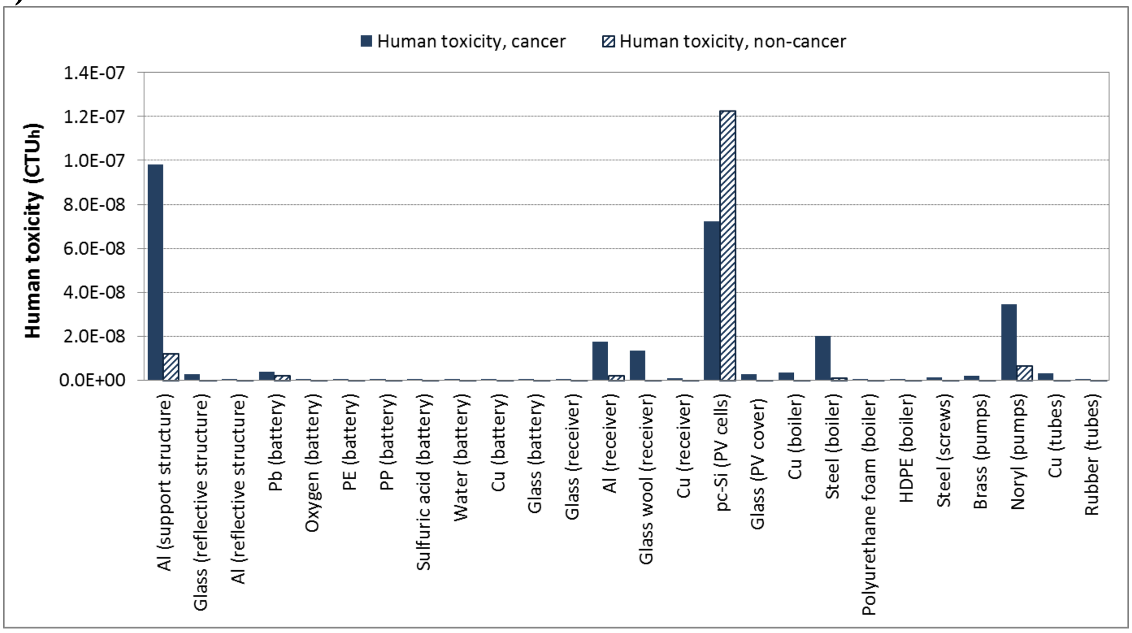
2) In terms of Human toxicity/non-cancer, the PV cells show the highest impact (remarkably higher than the other components/materials).

3) By taking into account both Human toxicity/cancer and Human toxicity/non-cancer, the components/materials with two highest values are the aluminium support structure and the PV cells.

4) Concerning Ecotoxicity, the Noryl (for the pumps), the PV cells and aluminium support structure are the components/materials with the first (62.5 CTU_e), second (16.6 CTU_e) and third (3.9 CTU_e) highest impact, respectively. It can be noted that the Noryl (for the pumps) shows an impact considerably higher in comparison to the other components/materials.

The reasons for the high impact of the PV cells and aluminium (primary) have been previously discussed (subsections 3.1.1, 3.1.2 and 3.1.3). In the case of Noryl, polyphenylene sulfide has been considered and during the manufacturing phase of this material the greatest part of the impact is due to benzene chlorination and P-dichlorobenzene production (Sources: SimaPro; ecoinvent). Hischier (2007) presented a report about the plastics in ecoinvent. It was noted that polyphenylene sulphide is an important thermoplastically processable representative of the group of poly(acrylene sulphides). With respect to the production process, the main raw materials, the production energy as well as estimations about the emissions have been taken into account. The process data include raw materials and chemicals, energy, water, transport and infrastructure, emissions to air and water, waste.

a)



b)

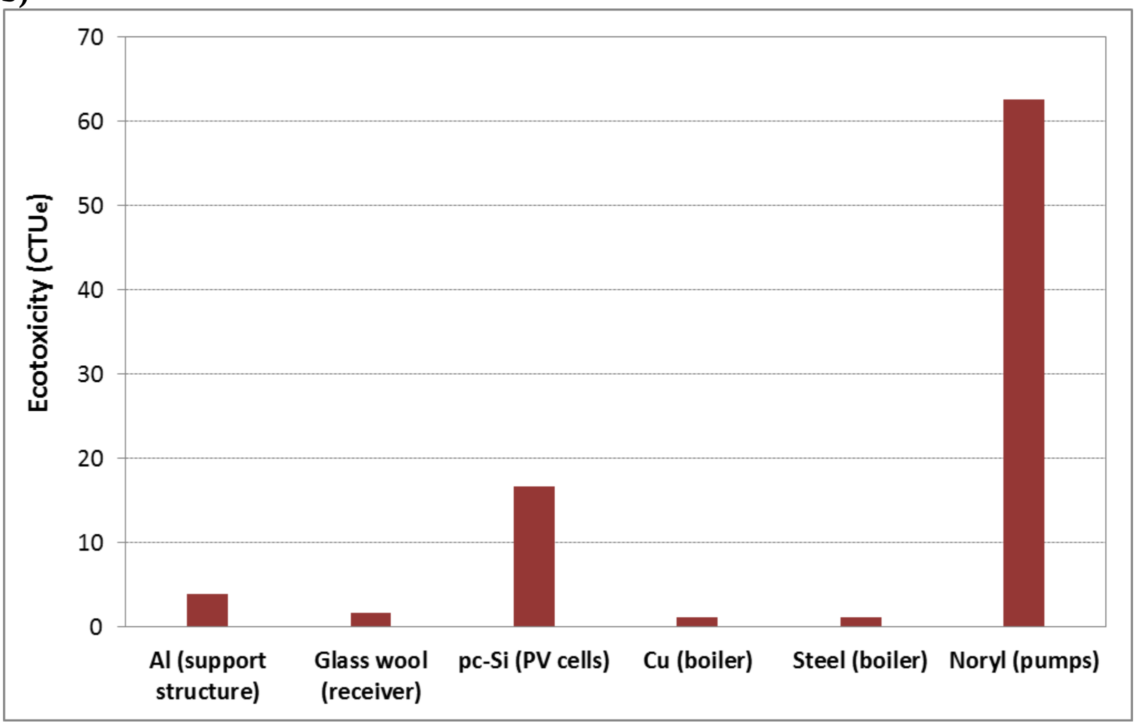


Figure 8. USEtox in terms of: a) Human toxicity/cancer and Human toxicity/non-cancer (in CTU_h), b) Ecotoxicity (in CTU_e). Phase of material manufacturing for certain components/materials of the PVT system, based on the LCI of Table 2.

3.1.8. Aluminium support structure and discussion about recycling

Based on the findings that have been previously presented, it can be seen that according to GWP (Figure 3), CED (Figure 4), for most of the midpoint categories of ReCiPe (Table 2) as well as based on ReCiPe endpoint single-score (Figure 5), ReCiPe endpoint with characterization (Figure 6), EF single-score for the category of Carbon dioxide (Figure 7a) and USEtox Human toxicity/cancer (Figure 8a), the aluminium support structure shows a considerable impact and, in certain cases, this impact is remarkably higher in comparison to other components/materials of the PVT system. Nevertheless, it should be taken into account that for the calculations of subsections 3.1.1-3.1.7 recycling has not been included. Calculations with recycling of certain materials (metals, glass, plastics) have been done. In subsection 3.2 these results are presented and it can be seen that recycling can remarkably improve the environmental profile of the PVT system.

The environmental performance of the PVT system can be improved for example by using less aluminium (or by utilizing alternative materials with lower impact). The concentrating solar thermal part and the reflective surface include considerable amounts of materials, especially aluminium and glass (Table 2). Certainly, by means of recycling the impact of these materials can be considerably reduced. The influence of aluminium recycling on the environmental performance of a solar thermal collector has been examined for example by Ardente et al. (2005) (it was highlighted that aluminium presents a considerable effect on the global energy balance and this is mainly due to the high specific energy consumption for aluminium production). The sustainable management of aluminium has become very important because there is an exponential growth in terms of its global demand. Aluminium recycling is a critical issue since it prevents the valuable material stream from going to landfill (Soo et al., 2018).

3.2. EPBTs, ReCiPe PBTs and comparisons with the literature

The calculations for the present PVT system show EPBTs of 1.6 and 0.6 years, for the scenario «without recycling» and «with recycling», respectively. Therefore, it can be observed that recycling considerably reduces EPBT.

Concerning findings from the literature, Tripanagnostopoulos et al. (2005) evaluated several PVT configurations (with/without glazing, with/without reflector, etc.) for water heating (installations for building roofs) and the results (for replacing electricity only) showed EPBTs ranging from 0.8 to 3.8 years, depending on the scenario. Battisti and Corrado (2005) investigated several PVT systems and the results showed EPBTs ranging from 1.7 years (PVT for domestic water heating, replacing electricity) to 2.8 years (PVT for space heating). Moreover, Dubey and Tiwari (2008) calculated an EPBT of 1.3 years for a PVT solar water heater for domestic applications.

With respect to review articles, Bhandari et al. (2015) presented a systematic review and meta-analysis about EPBT of PV systems. It was noted that the mean harmonized EPBT value varied from 1.0 to 4.1 years; from lowest to highest EPBTs, the following ranking (for the PV modules) was found: cadmium telluride, copper indium gallium diselenide, amorphous silicon, poly-crystalline silicon and mono-crystalline silicon (Bhandari et al., 2015). Moreover, in the review article of Lamnatou and Chemisana (2017) about PVT LCA, it was mentioned that according to LCA studies on BA PVT configurations, the EPBTs ranged from around 1 to 4 years, depending on the studied case (type of PV cells, lifespan, type of working fluid, etc.).

Based on the EPBTs of the literature, it can be seen that there is quite good agreement with the present results. However, it should be taken into account that a direct comparison is not possible due to differences (e.g. in terms of the boundaries, the specific components of each system, etc.) between the present study and the literature.

With respect to ReCiPe PBTs, the results for the PVT system show values of 17 and 8.4 years, for the scenario «without recycling» and «with recycling», respectively. The high ReCiPe PBTs are associated with the low avoided ReCiPe impact ($I_{out.a}$ of equation (2)). The low avoided ReCiPe impact is related to the specific characteristics of France’s electricity mix (high penetration of nuclear energy, low CO_2 emissions, etc.) (Source: EDF (Electricité de France)). At this point it should be noted that in the study of Lamnatou et al. (2017b) about a BICPV (building-integrated concentrating photovoltaic) with 3D cross compound parabolic concentrator and geometric concentration ratio 3.6×, high ReCiPe PBTs in the case of French cities have been reported. Different cities were examined and the results (scenario without material replacement) showed ReCiPe PBTs: 1) Less than 5 years for Barcelona, Seville, London and Aberdeen, 2) 16.52 years for Marseille, 3) 29.58 years for Paris. Therefore, the value of 17 years ReCiPe PBT for the BA PVT system of the present study (climatic conditions of Ajaccio and France´s electricity mix) is close to the value for Marseille (16.52 years: climatic conditions of Marseille and France´s electricity mix) for the BICPV studied by Lamnatou et al. (2017b). Certainly, a direct comparison is not possible because the system of the present study is not BICPV; however, in both investigations (present study and Lamnatou et al. (2017b)) the use of France´s electricity mix results in high ReCiPe PBTs.

3.3. Additional comparisons with the literature

3.3.1. Comparisons in terms of the PVT without the batteries

In Table 5 the results of the present study (according to CED and GWP; BA PVT) are compared with the literature (for BA PVT and BIPVT systems) and it can be observed that, in general, there is a good agreement. In addition, by considering all the studies that are presented in Table 5 it can be seen that: 1) GJ/m^2 values range from 4.59 to 6.38, 2) t $CO_{2.eq}/m^2$ values range from 0.43 to 0.52.

Table 5. Comparisons between the present study (BA PVT) and the literature (BA PVT and BIPVT).

STUDY / TYPE OF BUILDING INTEGRATION	PV CELLS	WORKING FLUID	SYSTEM, APPLICATION	ENVINMENTAL ISSUES	SURFACE	IMPACT PER m^2: PHASE OF MATERIAL MANUFACTURING
Present study / BA PVT	Multi-crystalline silicon	Water	BA PVT appropriate for off-grid applications	CED, GWP, ReCiPe, USEtox, etc.	15.49 m^2 (surface of the mirrors)	Values per m^2 of surface of the mirrors: Without batteries, With storage tank: **6.05 GJ_{prim}** (CED) Without batteries, Without storage tank: **5.67 GJ_{prim}** (CED) Without batteries, With storage tank: **0.52 t $CO_{2.eq}$** (GWP 100a) Without batteries, Without storage tank: **0.49 t $CO_{2.eq}$** (GWP 100a)
Tripanagnostopoulos et al. (2005) / BA PVT	Multi-crystalline silicon	Water	PVT system (with glazed covering and aluminium reflector) on horizontal roof	Embodied energy, $CO_{2.eq}$ emissions, etc.	30 m^2 (aperture surface area)	Expected values per m^2 of aperture surface area: **4.94 GJ** LHV **0.43 t $CO_{2.eq}$** (GWP 100a)
Kamthania and Tiwari (2014) / BIPVT	Mono-crystalline silicon	Air	Semi-transparent hybrid PVT double-pass façade	EPBT, CO_2 mitigation, etc.	12 units of (1.2 × 0.62) m^2 each of them	Expected value per m^2: **6.38 GJ**
Sun (2014) / BIPVT	Mono-crystalline silicon	Water	Residential home integration; Roof	EPBT, CED, GWP 100a, etc.	Solar cells	Values for 1 m^2 solar cell: **4.59 GJ** (CED) **0.43 t $CO_{2.eq}$** (GWP 100a)
Battisti and Corrado (2005) / Several PVT configurations	Multi-crystalline silicon	Air	PVT systems for roofs	Embodied energy, $CO_{2.eq}$ emissions, etc.	9.4 m^2 active surface for 1 kW_p	Values for 1 m^2 of module (PV module production): **5.15 GJ** LHV **0.46 t $CO_{2.eq}$**

3.3.2. Comparisons in terms of the batteries

For the lead-acid batteries (LCI of Table 2), CED and GWP 100a have been calculated to be 12.25 MJ_{prim} and 0.56 kg $CO_{2.eq}$ (per kg of battery), respectively. For the above mentioned impacts, the main contributors are the production of lead, polyethylene and polypropylene. More specifically, lead treatment of scrap acid battery and sodium hydroxide present a remarkable impact during lead production. Furthermore, for the production of polyethylene and polypropylene, a considerable contribution to the total impacts is related to incineration processes and hazardous waste (Sources: SimaPro 8; ecoinvent 3).

With respect to the literature, the database ICE (2011) presented values of 10 MJ/kg (embodied energy) and 0.58 kg $CO_{2.eq}$/kg (embodied carbon) for recycled lead and it was highlighted that scrap batteries are a main feedstock in the case of recycled lead. Sullivan and Gaines (2012) estimated the energy for material production of industrial lead-acid batteries. A value of 26 MJ/kg was found for the scenario «without recycling» and it was noted that this value can be reduced to 12.7 or 7.0 MJ/kg by adopting recycling, depending on the percentage of the recycled materials. In addition, it was mentioned that lead-acid batteries are highly recycled and the new lead-acid batteries present high percentages of recycled content (Sullivan and Gaines, 2012).

3.3.3. Comparisons in terms of the storage tank

In Table 6, the results for the storage tank (only materials for the storage tank: LCI presented in Table 2) are compared with the literature. From Table 6 it can be seen that: 1) In general, there is quite good agreement between the present findings and those of the literature, 2) By having as reference a storage tank of 300 l, the values of GJ_{prim} range from 4.3 to 7.5 and the values of t $CO_{2.eq}$ range from 0.3 to 0.5.

Table 6. Comparisons between the present results (in terms of the storage tank (capacity: 300 l)) and the literature.

STUDY/ SOURCE	ADDITIONAL INFORMATION	CAPACITY OF THE WATER STORAGE TANK (l)	RESULTS (FOR A STORAGE TANK OF 300 l)
Present study	BA PVT with water storage tank	300	**5.9 GJ_{prim}** (CED) **0.3 t $CO_{2.eq}$** (GWP 100a)
Ecoinvent 3	Hot water tank (market)	600	Expected results for 300 l: **5.9 GJ_{prim}** (CED) **0.5 t $CO_{2.eq}$** (GWP 100a)
de Laborderie et al. (2011)	Solar thermal collectors with water storage tank for domestic hot water	300	**7.5 GJ_{prim}** (non-renewable) (approximate value) **0.4 t $CO_{2.eq}$** (approximate value)
Sun (2014)	BIPVT with water storage tank	600	Expected results for 300 l: **4.3 GJ_{prim}** (CED) **0.4 t $CO_{2.eq}$** (GWP 100a)

4. CONCLUSIONS

The environmental profile of a PVT system with thermal and electricity storage that has been developed and experimentally tested in France (University of Corsica) has been examined. The studied system combines non-concentrating PV modules with concentrating solar thermal. The environmental performance of the system has been assessed for the Mediterranean climatic conditions of Ajaccio (France).

The evaluation has been based on different methods and environmental indicators and the results (phase of material manufacturing; scenario «without recycling») reveal that according to:

- GWP and CED

- Most of the midpoint categories of ReCiPe

- ReCiPe endpoint single-score and ReCiPe endpoint with characterization

- EF single-score (for the category of Carbon dioxide)

- USEtox Human toxicity/cancer

the aluminium support structure presents a remarkable impact and, in certain cases, this impact is considerably higher in comparison to the other components/materials of the PVT system.

Moreover, the results based on ReCiPe endpoint single-score (scenario «without recycling») demonstrate that the copper-based components (receiver; boiler; tubes) show the second highest score. Furthermore, the PV cells are responsible for the third highest ReCiPe endpoint single-score.

According to ReCiPe endpoint with characterization (scenario «without recycling»), the components with the highest DALY and (species.yr) are the aluminium-based ones. The two aluminium-based components (support structure; receiver) show total values of 0.015 DALY and 4.9×10^{-5} (species.yr).

With respect to EF findings (scenario «without recycling»), for EF/Carbon dioxide the aluminium support structure presents the highest score (remarkable higher than the other components) and for EF/Nuclear the PV cells show the highest score. Based on EF/Carbon dioxide the score of the aluminium support structure is approximately 3 times higher than that of the PV cells. According to EF/Nuclear, the total Pts for the PV cells are almost double than the total Pts for the aluminium support structure.

Regarding USEtox Human toxicity/cancer (scenario «without recycling»), the aluminium support structure, the PV cells and the Noryl (for the pumps) are the components/materials with the first, second and third highest impact, respectively. Regarding USEtox Ecotoxicity, the Noryl (for the pumps) and the PV cells present the first and second highest impact, respectively. More analytically, the Noryl (for the pumps) shows a value of 62.5 CTU_e that is considerably higher in comparison to the other components/materials.

By using recycling, the environmental profile of the PVT system shows a considerable improvement. The results demonstrated that by means of recycling (for metals, glass and plastics), EPBT is reduced from 1.6 to 0.6 years and ReCiPe PBT is reduced from 17 to 8.4 years.

In addition, comparisons with the literature have been presented (based on different methods and environmental indicators) and, in general, a good agreement has been observed. For the comparisons different options have been adopted: i) the PVT system itself, ii) separate components of the system (batteries; storage tank).

By taking into account the fact that in the literature there are few PVT LCA studies which are based on multiple life-cycle impact assessment methods and environmental indicators, it can be seen that the present article offers useful information in the frame of cleaner production technologies.

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